

AD-A058 344

CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAI--ETC F/G 8/11  
METHODS FOR SEISMIC STRENGTHENING OF BUILDINGS.(U)  
JUL 78 J M LYBAS

UNCLASSIFIED

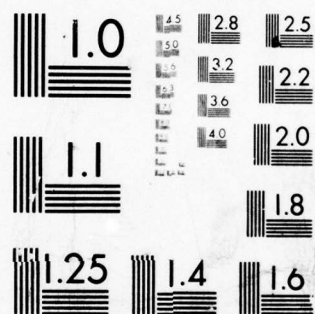
CERL-IR-M-249

NL

| OF |

AD  
A058 344





MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

AD A 058344

construction  
engineering  
research  
laboratory

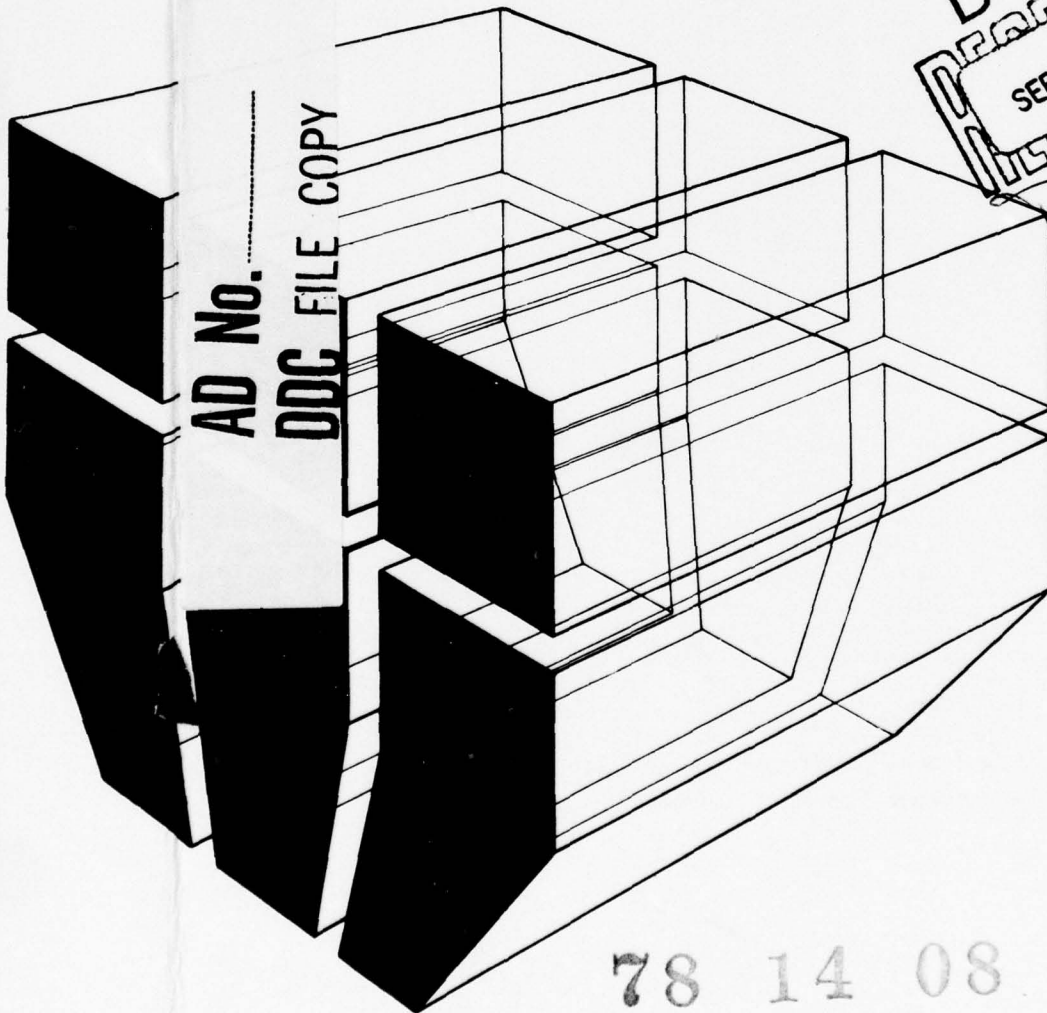
~~LEVEL~~

12

INTERIM REPORT M-249  
July 1978

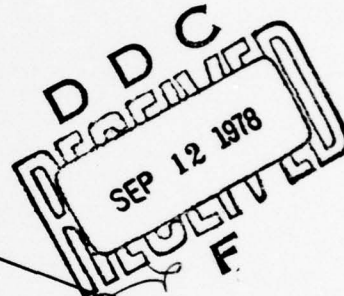
Design Guide for Seismic Strengthening of Existing Facilities

METHODS FOR SEISMIC STRENGTHENING OF BUILDINGS



AD No.

DDC FILE COPY



by  
J. M. Lybas

78 14 08 047



Approved for public release; distribution unlimited.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official indorsement or approval of the use of such commercial products. The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

***DESTROY THIS REPORT WHEN IT IS NO LONGER NEEDED  
DO NOT RETURN IT TO THE ORIGINATOR***



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CERL-IR-M-249	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) METHODS FOR SEISMIC STRENGTHENING OF BUILDINGS		5. TYPE OF REPORT & PERIOD COVERED INTERIM
7. AUTHOR(s) J. M. Lybas		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS CONSTRUCTION ENGINEERING RESEARCH LABORATORY P.O. Box 4005 Champaign, IL 61820		8. CONTRACT OR GRANT NUMBER(s)
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 4A762731AT41-04-003		11. CONTROLLING OFFICE NAME AND ADDRESS
12. REPORT DATE July 1978		13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE		
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. 12 30 p.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) 9 Interim rept. 10 John M. Lybas		
18. SUPPLEMENTARY NOTES Copies are obtainable from National Technical Information Service Springfield, VA 22151		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) epoxy seismic resistance strengthening methods		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report provides guidance for engineers to use in strengthening buildings found to be deficient in seismic resistance. The guidance is intended to serve as the basis for criteria for determining the suitability of specific strengthening schemes for a building and applying specific strengthening methods.		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Block 20 continued.

Various strengthening methods which have been used in the past are reviewed, with emphasis given to those most applicable to Army needs. Detailed guidelines for the application of two methods—pneumatic application of concrete and use of epoxy compounds—are provided, along with advantages and disadvantages of each.

ACCESSION for	
NTIS	Section <input checked="" type="checkbox"/>
DDC	Section <input type="checkbox"/>
UNAVIM INDEX	Section <input type="checkbox"/>
1-5110.1	
BY	
DISTRIBUTION/AVAILABILITY CODES	
1/1	SPECIAL
A	

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

## FOREWORD

This investigation was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project 4A762731AT41, "Design, Construction and Operation and Maintenance Technology for Military Facilities"; Task 04, "Military Construction Technology"; Work Unit 003, "Design Guide for Seismic Strengthening of Existing Facilities." The applicable QCR is 1.03.003. The OCE Technical Monitor was G. M. Matsumura, DAEN-MCE-A.

This investigation was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (CERL). The principal investigator for the project was Mr. John M. Lybas. Dr. G. R. Williamson is Chief of EM. ✓

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.



## CONTENTS

DD FORM 1473	1
FOREWORD	3
LIST OF TABLES AND FIGURES	5
1 INTRODUCTION .....	7
Background	
Purpose	
Approach and Scope	
Mode of Technology Transfer	
2 STRENGTHENING PROBLEM .....	7
Need for Strengthening	
Methods for Strengthening	
Practical Considerations in Strengthening	
3 PNEUMATIC APPLICATION OF CONCRETE .....	8
Definition	
Past Applications	
Methods of Application	
Engineering Properties	
Guidelines for Application	
Advantages and Problems	
4 APPLICATIONS FOR EPOXY COMPOUNDS .....	16
Definition	
Past Applications	
Engineering Properties	
Guidelines for Application	
Associated Problems	
5 CHOICE OF A STRENGTHENING SCHEME .....	27
6 CONCLUSIONS .....	27
REFERENCES	27
DISTRIBUTION	

## TABLES

Number		Page
1	Examples of Epoxy Strength for Several Bridges in New York State	18
2	Ranges of Various Engineering Properties of Typical Cured Commerical Polyamide Epoxy Resin	19
3	Ranges of Maximum Ambient Temperatures for Satisfactory Continuous Service of Typical Cured Commercial Polyamide-Cured Epoxy Resin	20
4	Physical and Chemical Reactions of Typical Cured Commercial Polyamide Epoxy Resin (Rigid)	20
5	Comparison of Properties of Cementitious Grout and Epoxy Resin Containing Filler	21
6	Testing Standards for Epoxy Formulations	22

## FIGURES

1	Strengthening of Walls	9
2	Strengthening of Concrete Columns and Beams	10
3	Strengthening of Masonry Wall	11
4	Specimen for Arizona Slant Shear Test	23

6/2/21



# METHODS FOR SEISMIC STRENGTHENING OF BUILDINGS

## 1 INTRODUCTION

### Background

Army bases contain a wide variety of buildings which, although built in conformance to building codes in effect at the time of their construction, possess widely varying degrees of resistance to seismic loading. In the event of a major earthquake, many of these buildings could pose hazards to life or threaten the proper functioning of the military facility. The alternatives for buildings having inadequate seismic resistance are to endure the risks to life and functionality, to replace the building, or to strengthen the building to attain a more acceptable level of risk. The strengthening of existing buildings for seismic loading requires techniques for and application of strengthening methods. Therefore, guidelines are needed on the techniques for and application of specific strengthening methods.

### Purpose

The purpose of this study is to develop guidance for engineers to use in strengthening buildings found to be deficient in seismic resistance. The guidance is intended to serve as the basis for criteria for determining the suitability of specific strengthening schemes for a building and for the application of specific strengthening methods.

### Approach and Scope

This report is directed specifically toward the strengthening of buildings for seismic loading. Reinforced concrete and, to an extent, unit masonry are emphasized because these materials are prevalent in Army buildings.

Chapter 2 briefly describes the strengthening methods that have been used in the past. Chapters 3 and 4 concentrate on the methods most applicable to Army needs. Detailed guidelines for applying the methods are provided, along with advantages and disadvantages. Chapter 5 presents general guidelines for choosing a strengthening scheme.

### Mode of Technology Transfer

The general information and methodology described in this report will be transferred to Army field personnel through incorporation, along with information on

the seismic strengthening of other classes of facilities, into a technical manual in the 5-809 series.

## 2 STRENGTHENING PROBLEM

### Need for Strengthening

A particular structure's need for seismic strengthening should be determined using the general considerations discussed in U. S. Army Construction Engineering Research Laboratory (CERL) Technical Report M-213,<sup>1</sup> along with structural analysis calculations. The adequacy of each wall or frame in the structural system should be determined by comparing its computed strength with the loads assigned to it in the structural analysis. The structural analysis should consider the capacity of the complete structural system. The adequacy of each proposed strengthening scheme should be evaluated through an analysis of the revised structural system, comparing the force requirement with the strength of each wall or frame.

### Methods for Strengthening

When the required forces in frames or walls are larger than their computed capacities, strengthening is in order if life safety and functioning of the facility after an earthquake are to be assured. Strengthening methods applied in the past include addition of section to flexural members (beams and columns); addition of external stirrups to flexural members to account for deficiency in shear strength; injection of various materials into cracked, deteriorated, or void-ridden walls; addition or thickening of walls; thickening of floor slabs; and addition of section to reinforced concrete joints.

### Practical Considerations in Strengthening

Probably the most obvious approach to strengthening is to strengthen directly those members that are shown by structural analysis to be deficient. This approach often has several disadvantages, however. The strengthening of walls or frame members on the interior of the building requires interior construction work with its accompanying noise, dirt, and safety problems. For a hospital or residential building, such activity may

<sup>1</sup> J. M. Lybas, *Guidelines for Evaluating the Seismic Resistance of Existing Buildings*, Technical Report M-213 (U.S. Army Construction Engineering Research Laboratory [CERL], 1977), Chapter 2.

require vacating the building, which is often unacceptable. Less disruptive strengthening approaches must therefore be taken or construction phasing must be employed to maintain functional operations.

A second approach for rendering a building seismically adequate is to decrease the load that the deficient member is required to carry. An obvious way to accomplish this is to decrease the weight of the building. This is often not feasible, although in certain cases one or more of the upper stories could conceivably be removed. The load in a given wall or frame may also be reduced by effecting a transfer of load from the structurally deficient wall or frame to some other wall or frame. This transfer of load can be accomplished by stiffening other walls or frames relative to the structurally deficient one. In general, this stiffening will also increase the strength of those other walls or frames, enabling them to carry the additional load. Such an approach allows buildings to be upgraded through strengthening, adding, or thickening exterior walls. The seismic loads are transferred from overloaded walls or frames into the stiffened and strengthened exterior walls. The major advantage of strengthening by altering exterior walls is that such work can often be done while the building (even a hospital) remains operational.

Based on these considerations, this report emphasizes strengthening structural walls. The most straightforward variation of this approach would be the addition of conventionally cast reinforced-concrete walls. This method, however, entails the expense and disruption of formwork construction around the building. Furthermore, this method does not address the problem of upgrading an existing wall of inferior quality (i.e., cracked or deteriorated in some other respect).

Attention has therefore been focused on two alternative techniques: the pneumatic application of concrete (Chapter 3) and the use of epoxy compounds (Chapter 4). The former is an efficient means of thickening old walls and adding new walls. The latter can be used to strengthen old walls and to bond new walls to old walls.

### **3 PNEUMATIC APPLICATION OF CONCRETE**

#### **Definition**

Pneumatic application of concrete includes any procedure in which mortar or coarse aggregate concrete is

deposited on a surface by force of compressed air. The method of application allows a very low water-cement ratio to be used, while the force of deposition results in great density, avoiding the need for formwork and producing a material of high bond and compressive strength. The process was originally used only with mortar, but it is now also used with concrete containing small-size coarse aggregate.<sup>2</sup>

#### **Past Applications**

Pneumatic application of concrete has been used to increase the thickness of existing walls and to enlarge the section of flexural members, as well as to add new walls and repair cracked or deteriorated walls as shown in Figures 1, 2 and 3. In general, the procedure's high cost limits its application to instances in which the advantages outweigh the extra costs. In many cases, the advantages are savings in formwork and freedom of shape. In the case of strengthening existing buildings, reduced impact on facility operation is another advantage counterbalancing the added cost.

#### **Methods of Application<sup>3</sup>**

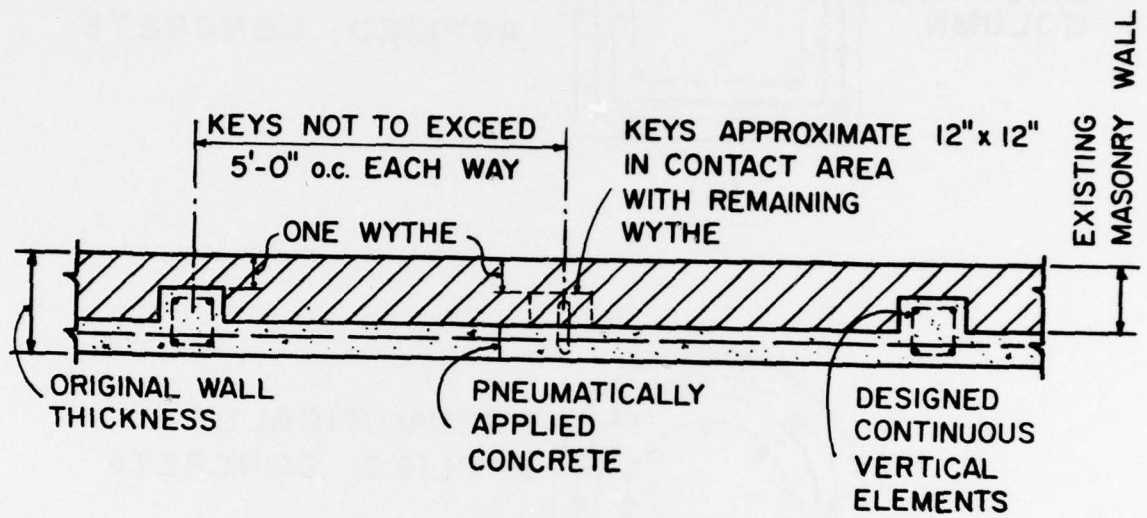
The pneumatic application of concrete is accomplished through either the wet or dry process. This section describes the two methods and lists their relative advantages and disadvantages.

##### *Dry Process*

In the dry process, the materials are mixed in the hopper to the proper proportions in a dry state. A control system feeds the dry material into the air hose at a constant rate. The material is blown under compressed air to a nozzle where water is added in the desired proportions. The machine is operated by a four-person crew consisting of a gun operator and one person each for the hopper, nozzle, and hose. The air pressure for machines of this type is normally 30 to 60 psi (207 to 414 kPa) and the water pressure for injection is normally 15 psi (103 kPa) greater than the air pressure. Machines of this type have been built to convey material horizontally for 500 and vertically for 100 m. Hence, the heavy, noisy hopper and compressor machinery can be placed on the ground outside the building being worked on while concrete is being placed in the interior of the building or on an upper story. This feature saves scaffolding costs and is obviously important if the building is in operation while the work is being performed.

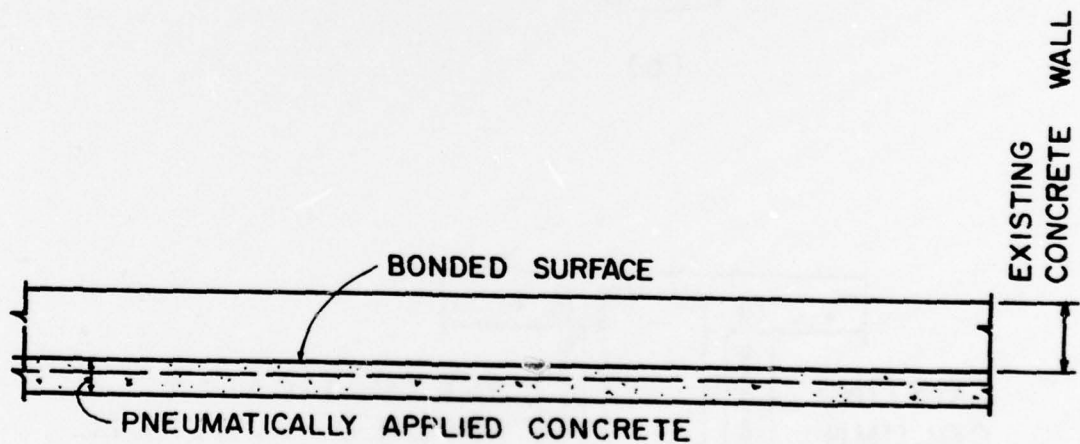
<sup>2</sup>D. F. Orchard, *Concrete Technology*, Vol 2 (John Wiley and Sons, Inc., 1973), pp 380-398.

<sup>3</sup>Much of the information in this and the following section was drawn from D. F. Orchard, *Concrete Technology*, Vol 2 (John Wiley and Sons, Inc., 1973), pp 380-398).



BRICK MASONRY

(a)

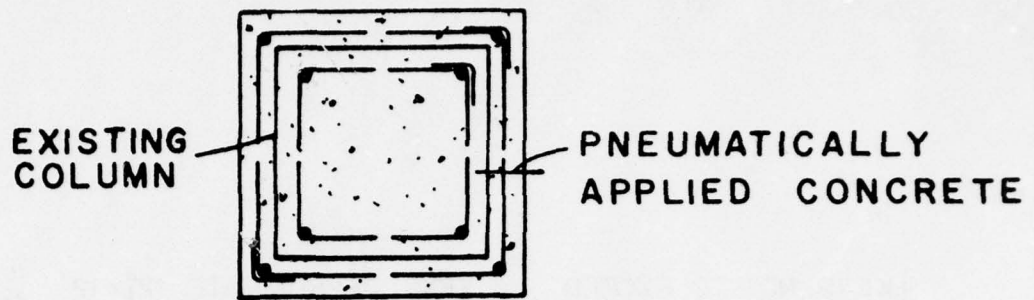


CONCRETE

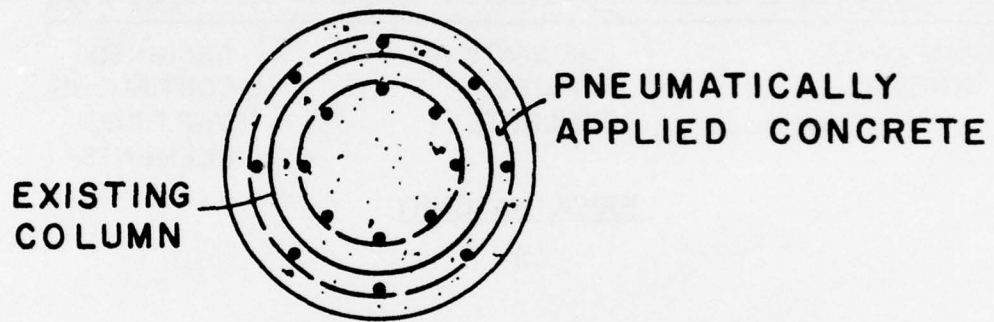
(b)

Figure 1. Strengthening of walls.

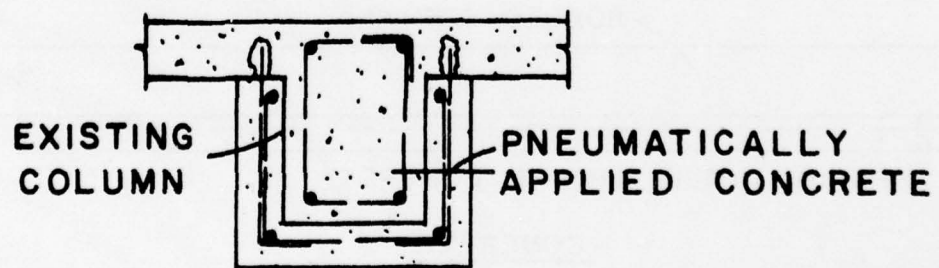




(a)



(b)



(c)

Figure 2. Strengthening of concrete columns and beams.

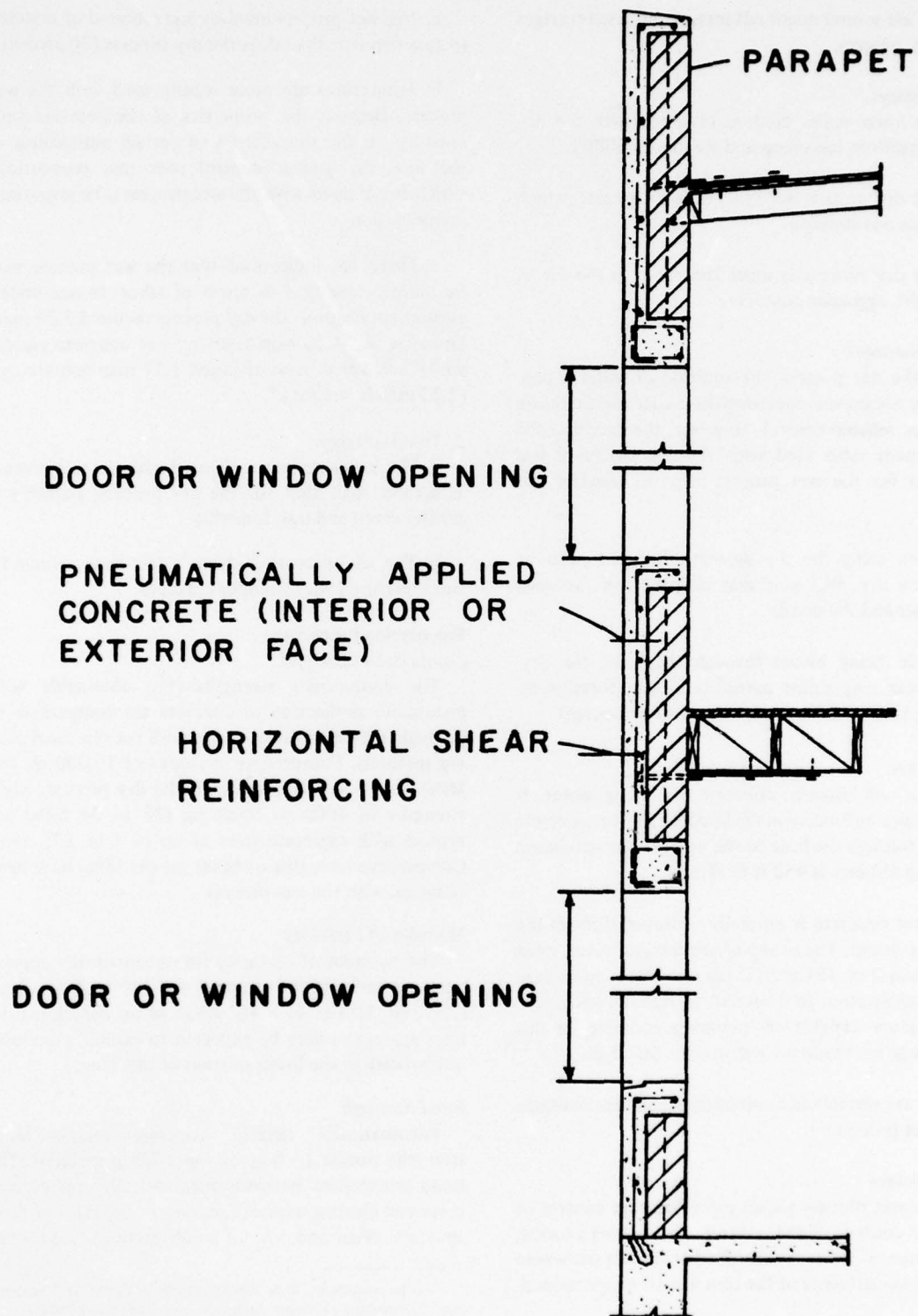


Figure 3. Strengthening of masonry wall.

There are several major advantages and disadvantages to the dry process.

#### 1. Advantages

a. The lower water content obtained with the dry process results in less creep and greater durability.

b. The dry process leads to a denser concrete, which often improves strength.

c. The dry process is more adaptable to the use of lightweight, aggregate concrete.

#### 2. Disadvantages

a. In the dry process, the addition of water is controlled by the person operating the nozzle and therefore under less reliable control. However, the fact that the water-cement ratio used with the dry process is less than that for the wet process helps to alleviate this problem.

b. When using the dry system, the sand must be completely dry. Wet sand may clog the hose between the hopper and the nozzle.

c. While being blown through the hose, the dry-process mix may suffer partial loss of uniformity, resulting in pockets of mix with low cement content.

#### Wet Process

In the wet process, concrete, including water, is proportioned and mixed in the hopper. The wet concrete is blown through the hose to the nozzle. The maximum conveying distance is 450 ft (137 m).

The wet concrete is generally conveyed through the hose by a pump. The slump of the mix, however, must be less than 2 in. (51 mm) if the concrete is to be suitable for application to a vertical surface. Development of machinery capable of pumping concrete in this slump range has made the wet process practical.

There are several major advantages and disadvantages to the wet process.

#### 1. Advantages

a. The wet process allows more accurate control of the water content of the concrete. In the wet process, the addition of water is controlled at the hopper where the other constituents of the concrete are proportioned.

b. The wet process presents a smaller dust hazard than the dry process.

c. The wet process involves less rebound of material (5 to 8 percent) than does the dry process (30 percent).

d. Admixtures are more readily used with the wet process. Because the properties of concrete are very sensitive to the proportions of certain admixtures in the mix, the greater control over mix proportions which is obtained with the wet process is an important consideration.

e. There are indications that the wet process may be more economical in terms of labor. In one underground application, the dry process required 3.21 man-hours/cu yd (4.20 man-hours/m<sup>3</sup>) of concrete placed, while the wet process required 1.77 man-hours/cu yd (2.22 man-hours/m<sup>3</sup>).<sup>4</sup>

#### 2. Disadvantages

a. The water cement ratio used with the wet process is greater than that for the dry process, resulting in greater creep and less durability.

b. The wet process leads to a less dense concrete, and therefore lower strength concrete.

#### Engineering Properties

##### Compressive Strength

The compressive strengths ( $f'_c$ ) obtainable with pneumatic application of concrete are comparable to (or higher than) those obtained with conventional casting methods. Compressive strengths of 10,000 psi (69 MPa) have been obtained with the dry process, while strengths of 4000 to 5000 psi (28 to 34 MPa) are typical with aggregate sizes of up to 1 in. (25 mm). Compressive strengths of 6000 psi (41 MPa) have been obtained with the wet process.

##### Modulus of Elasticity

The modulus of elasticity for pneumatically applied concrete varies in the range of  $4 \times 10^6$  to  $6 \times 10^6$  psi ( $28 \times 10^3$  MPa to  $41 \times 10^3$  MPa). Mixes containing the finer aggregates may be expected to exhibit a modulus of elasticity in the lower portion of this range.

##### Bond Strength

Pneumatically applied concrete attains bond strengths similar to that of the original material. The bond is excellent between pneumatically applied concrete and existing concrete, masonry, and steel surfaces that are clean and free of loose particles.<sup>5</sup> However,

<sup>4</sup>H. N. Steenson, "Fast Set Shotcrete in Concrete Construction," *American Concrete Institute Journal* (June 1974).

<sup>5</sup>"Recommended Practice of Shotcreting (ACI 506-66)," *ACI Manual of Concrete Practice*, Part 3 (1974).



little engineering data on the actual bond strength exist. The high bond strength is probably attributable to the high velocity of application. Several warnings are in order, however. Since the bond strength depends partially on the velocity of application from the nozzle, it is somewhat sensitive to the skill of the crew. Also, when certain admixtures are used to accelerate hardening of the concrete (accelerators), the concrete may not bond well to very wet surfaces. Finally, steel surfaces should be clean, and all surfaces should be free of loose particles.

#### Guidelines for Application

This section presents several general guidelines for pneumatic application of concrete. These guidelines generally apply to both constructing new walls and adding material to flexural members. They cover such topics as mix proportions, quality control, surface preparation, formwork and dimensional control, application of the concrete in multiple layers, rebound, curing, finishing, and reinforcement details. The procedures and cautions presented must be followed if the results of the strengthening work are to be satisfactory in terms of strength, durability, and appearance.

#### Mix Proportions<sup>6</sup>

Pneumatically applied concrete can be expected to obey the same water-cement ratio versus strength law as conventionally placed concrete. When the dry process is used, the water-cement ratio will generally be less than or equal to 0.30. When the wet process is used, the water-cement ratio will be somewhat higher. In general, too much water will cause the concrete to slump on vertical surfaces. Too little water will lead to wet concrete with poor adhesion.

In many cases, the relative proportions of cement and sand will be on the order of one part cement to three and one-half parts sand by dry volume. Mixes richer than one part cement to three parts sand should not be used. It is important to note that rebound material contains a significantly greater amount of sand relative to cement than does the overall concrete. Concrete mixed to proportions of one part cement to three and one half parts sand in the hopper may have one part cement to three parts sand in place.

Many of the admixtures used for conventionally placed concrete can be used with pneumatically applied concrete. However, control of the mix proportions in

pneumatic application of concrete is not as good as that for conventional casting. Thus, admixtures whose effects are very sensitive to mix proportion should not be used.

Use of accelerator admixtures to speed the rate of hardening for vertical work presents a major problem. Although such accelerators also tend to reduce rebound, they can increase the cost of the concrete by 50 percent. Until recently, accelerators could not be used with the wet process; the concrete could set in the hose between hopper and nozzle. In a recent application, however, the accelerator was added at the nozzle by forming the admixture into a log of solid material and feeding it at a controlled rate into a grinding mechanism for addition to the concrete.<sup>7</sup>

#### Quality Control

The American Concrete Institute (ACI) recommends that preconstruction testing be accomplished by applying concrete to 30 × 30 in. (762 × 762 cm) test panels in the same manner that it is applied to the building and testing 3 in. (76 mm)-diameter cores and 3-in. (76-mm) cubes taken from the panel.<sup>8</sup> The cores and cubes should be soaked in water for at least 40 hours before testing.

For daily quality control, ACI recommends gunning concrete to a test panel in the same manner that the concrete is being applied to the building and cores or cubes from the panel tested. At least one panel 18 × 18 × 3 in. (457 × 457 × 76 mm) should be prepared for each 50 cu yd (38 m<sup>3</sup>) of concrete applied to the building, except that at least one panel per shift should be prepared.

ACI does not recommend use of impact hammers, ultrasonic equipment, and other nondestructive testing methods for quality control in their specifications.

#### Surface Preparation

Certain procedures must be followed in preparing the surface onto which the new concrete is to be applied in order to achieve proper adhesion between old and new concrete. All loose or damaged concrete must be removed and all corners should be tapered. Porous material should be kept damp for several hours before ap-

<sup>7</sup>H. N. Steenson, "Fast Set Shotcrete in Concrete Construction," *American Concrete Institute Journal* (June 1974).

<sup>8</sup>"Specification for Materials, Proportioning, and Application of Shotcrete," Report of ACI Committee 506, *American Concrete Institute Journal* (December 1976).

<sup>6</sup>Much of the information in this section was drawn from D. F. Orchard, *Concrete Technology*, Vol 2 (John Wiley and Sons, Inc, 1973), pp 380-398.

plication of the new concrete, but the new material should not be deposited on standing or running water. Only dampness is recommended.

#### *Formwork and Dimensional Control*

**Formwork Needs.** Pneumatic-application of concrete does not require extensive formwork, as do more conventional methods. For constructing new walls, only one surface of formwork is needed to serve as a backing on which to shoot the concrete. When thickening an existing wall or repairing a damaged wall, shooting can be performed directly against the existing wall (cleaned and free of loose particles). Formwork for columns should be provided on two adjacent sides, although when the width is greater than one and one-half times the depth, columns have been formed on three sides.<sup>9</sup> Pilasters may be formed on two adjacent or opposite sides.<sup>10</sup>

The function of the formwork is to resist the impact of concrete, yet permit escape of air and rebound.<sup>11</sup> The forms are often made of plywood, although other materials have been used.<sup>12</sup> Often, the forms need not be as strong as those used in conventional casting procedures. For thin sections, this can be a major advantage.<sup>13</sup>

A major factor in economy of construction is often the length of time that forms must remain on the newly placed concrete. ACI<sup>14</sup> recommends two ways of achieving rapid retrieval of forms when concrete is applied pneumatically: (1) covering the forms with a polyethylene membrane, and (2) applying a coat of an accelerator to the forms. A mix without admixtures can then be applied, and the concrete will still harden rapidly enough for the efficient use of the forms.

**Dimensional Alignments.** Wires known as ground wires should be strung horizontally at several levels and

vertically at several sections to serve as guides for achieving the proper thickness and alignment for the in-place concrete. Hard steel 18 to 20 gage piano wire is often used for this purpose.<sup>15</sup> If proper control of alignment and thickness is to be maintained, the ground wires must remain secure and taut; hence, the wires must have adjusting devices for tightening.

Finally, the formwork itself must be well secured and aligned if proper dimensional control is to be maintained.

**Scaffolding.** For vertical elements, shooting is best done horizontally; hence, scaffolding strong enough to support the crew and necessary equipment is generally needed. However, since the hose from hopper to nozzle can convey concrete vertically, much equipment, including the hopper and the compressor, need not be placed on the scaffold.

**Application of Multiple Layers.** Pneumatic application of concrete is generally done only to a thickness of 1 to 1½ in. (25 to 38 mm) before the concrete is permitted to harden.<sup>16</sup> The primary concern in determining the above limitation is that the applied concrete not sag.<sup>17</sup> In wet weather, with little reinforcement in the added portion of the wall, this maximum thickness may be as low as ¾ in. (19 mm); in dry weather, with a high reinforcement ratio, layers 3 in. (76 mm) thick have been deposited.<sup>18</sup> However, with the use of admixtures to accelerate hardening, layers 6 to 8 in. (152 to 203 mm) thick have been deposited.<sup>19</sup>

In many cases, an additional wall thickness of 8 in. (203 mm) or more may be desired. The use of admixtures for rapid hardening may not be desirable because of cost, the limitations of the equipment being used, or other factors unique to the particular job. In such cases, the concrete must be applied in multiple layers, with each layer being permitted to harden before the next is applied.

<sup>9</sup>M. K. Hurd, *Formwork for Concrete*, Special Publication No. 4 (American Concrete Institute, 1973).

<sup>10</sup>Hurd.

<sup>11</sup>"Specification for Materials, Proportioning, and Application of Shotcrete," Report of ACI Committee 506, *American Concrete Institute Journal* (December 1976).

<sup>12</sup>"Recommended Practice of Shotcreting (ACI 506-66)," *ACI Manual of Concrete Practice*, Part 3 (1974).

<sup>13</sup>D. F. Orchard, *Concrete Technology*, Vol 2 (John Wiley and Sons, Inc., 1973), pp 380-398.

<sup>14</sup>J. M. Shilstone, "Site Cast Architectural Concrete—Architectural Surfaces by Shotcreting," *Concrete Construction* (November 1972).

<sup>15</sup>*ACI Manual of Concrete Practice*.

<sup>16</sup>D. F. Orchard, *Concrete Technology*, Vol 2 (John Wiley and Sons, Inc., 1973), pp 380-398.

<sup>17</sup>*ACI Manual of Concrete Practice*.

<sup>18</sup>Orchard.

<sup>19</sup>Orchard; "Recommended Practice of Shotcreting (ACI 506-66)," *ACI Manual of Concrete Practice*, Part 3 (1974); and H. N. Steenson, "Fast Set Concrete in Concrete Construction," *American Concrete Institute Journal* (June 1974).

The preparation required for application of a successive layer is similar to surface preparation of existing concrete or masonry, with some additional considerations. First, the layer is allowed to set. Next, loose particles, rebound, and laitance are removed by brooming. As for an existing concrete surface, sandblasting may be necessary to remove stubborn particles. The surface is then cleaned with an air-water jet and sounded for voids (drummy areas). Such voids in the pneumatically applied concrete can result from rebound and must be eliminated. The recommended procedure is to cut away the concrete in the drummy area to expose the void, which is then filled with concrete when the next layer is applied.<sup>20</sup> The final step in preparing a surface for a subsequent layer of concrete is to dampen it.

**Rebound.** When concrete is applied pneumatically, not all concrete passing through the nozzle remains on the surface of application. Often 15 to 30 percent of the concrete passing through the nozzle rebounds, or falls off the surface. It is because of this problem that pneumatic application of concrete is performed from the bottom to the top of the wall.<sup>21</sup> The rebound will fall onto a fresh surface and be blown away, rather than forming loose particles on a surface previously prepared to receive concrete. The rebound material is mostly sand, with little cement, and is thus likely to be weak. Since the material proportions and strength of the rebound are at best uncertain, it must not be reused.

Several factors influence the amount of concrete lost in rebound. Among these are the pressure of application of the concrete, the angle of application of the concrete, the mix proportions, the grading of the aggregates used in the concrete, and the reinforcement ratio for the portion of the wall being constructed.<sup>22</sup>

**Curing.** The procedures for curing pneumatically applied concrete are basically the same as those for conventionally placed concrete. Moist curing is necessary, as for conventionally placed concrete.<sup>23</sup> Newly applied surfaces must be kept wet for at least 7 days.<sup>24</sup> As for

conventionally placed concrete, pneumatically applied concrete must be protected from frost, wind, and sun during curing.<sup>25</sup> The temperature of the concrete must be kept above freezing for at least 7 days after placing.<sup>26</sup> The ACI recommended practice states that the above curing procedures are most critical for very thin layers, rough surfaces, and low-slump mixes.

**Finishing.** Finishing pneumatically applied concrete so that it becomes a smooth surface is often quite difficult, because of its low moisture content. This problem is especially acute with the dry process. Such surfaces are almost impossible to trowel. Screeding, however, is often possible. In many cases, a final coat of concrete, often 1/16 in. (2 mm) thick, is applied to obtain a finished texture.

**Reinforcement Details.** In general, the reinforcement must be positioned so as to minimize interference with the placing of the concrete. Assuring that concrete penetrates behind large reinforcing bars is often a major problem. For this reason, smaller bars are often used. Another problem associated with the positioning of reinforcement for pneumatically applied concrete is that of cover for the reinforcement. The surface of pneumatically applied concrete may be somewhat less even than that of conventionally placed concrete. When the section for the wall is designed, the planned cover for the reinforcement must be sufficient to account for this variation. One recommendation is that reinforcement in walls 1 1/2 in. (38 mm) thick be designed for a concrete cover of 3/4 in. (19 mm) and that reinforcement in walls 2 in. (5 mm) thick be designed for a concrete cover of 1 1/4 in. (32 mm).

**Miscellaneous Procedures.** Pneumatic application of concrete in walls should begin at the bottom of the wall and proceed upward. The first pass at each level should completely embed the reinforcement.<sup>27</sup>

To prevent sagging or sloughing off of the placed concrete, the layer thickness, method of support, air pressure, and water content must be controlled, and separation of the nozzle stream during placement must not be permitted.<sup>28</sup>

<sup>20</sup> ACI Manual of Concrete Practice.

<sup>21</sup> D. F. Orchard, *Concrete Technology*, Vol 2 (John Wiley and Sons, Inc., 1973), pp 380-398.

<sup>22</sup> Orchard.

<sup>23</sup> "The Guniting Technique," *Concrete Construction* (November 1965).

<sup>24</sup> ACI Manual of Concrete Practice.

<sup>25</sup> Orchard.

<sup>26</sup> ACI Manual of Concrete Practice.

<sup>27</sup> ACI Manual of Concrete Practice.

<sup>28</sup> "Specification for Materials, Proportioning, and Application of Shotcrete," Report of ACI Committee 506, *American Concrete Institute Journal* (December 1976).



Various specifications will be available for the equipment used to place the concrete. These specifications, or limitations, should be strictly adhered to. Two types of limitations often specified for equipment for pneumatic application of concrete relate to maximum conveyance distance (from hopper to nozzle) and distribution of aggregate sizes.<sup>29</sup>

#### Advantages and Problems<sup>30</sup>

A number of aspects of the pneumatic application of concrete may have a positive or negative impact on its suitability for a given project.

The positive aspects which make pneumatic application of concrete a viable means for the strengthening of buildings for seismic loading are:

1. The building is strengthened and can remain operational during the process.
2. The process requires less formwork than conventional placement.
3. The process requires only a small portable plant for mixing and placement.
4. The process results in excellent bond between the newly applied concrete and other materials, including old concrete.
5. The process allows heavy machinery to be placed far from the point of application. The concrete can then be conveyed through relatively thin pipes and hoses into otherwise inaccessible places.
6. Strengths obtained for the in-place concrete are comparable to those obtained with conventional casting techniques.

Among the negative aspects associated with the pneumatic placement of concrete are:

1. Reliable data on the in-place properties of concrete placed in such a manner are scarce.
2. The properties of the in-place material are highly dependent on the skill of the crew performing the work.

<sup>29</sup>D. F. Orchard, *Concrete Technology*, Vol 2 (John Wiley and Sons, Inc., 1973), pp 380-398.

<sup>30</sup>Much of the information presented in this section was drawn from Orchard and "Recommended Practice of Shotcreting (ACI 506-66)," *ACI Manual of Concrete Practice*, Part 3 (1974).

3. Although the total thickness of concrete that can be placed pneumatically is not limited technically, labor costs usually limit the thickness to 8 in. (203 mm).

4. Rebound must be continuously removed, requiring additional labor. Furthermore, the rebound is wasted material which cannot be reused.

5. In general, proper curing procedures are more critical to the final quality of the concrete than they are for conventionally placed concrete. The problem is primarily due to the low water content of the material.

6. Surface finishing is difficult, again due to the low water content.

7. Oversize pieces of aggregate must be screened out to avoid plugging the hose, again requiring extra labor.

8. Pneumatic deposition of concrete can often present problems in very confined spaces. Space is required for the nozzle itself, plus the turbulence caused by the expansion of compressed air leaving the nozzle.

9. The cost of admixtures used to accelerate the hardening of the concrete for vertical work is quite high.

## 4 APPLICATIONS FOR EPOXY COMPOUNDS

### Definition

An epoxy compound consists of a resin and a hardener. The components are stored separately. When mixed, they react exothermically to form a thermosetting plastic. The types of resin and hardener used and their mix proportions largely determine the properties of the final material. In addition, various additive materials, including reactive or nonreactive flexibilizers, plasticizers, diluents, and inert fillers, are used to tailor the properties of the hardened epoxy to the particular application. According to a report by ACI Committee 503,<sup>31</sup> following the advice of the manufacturer concerning the properties of any particular formulation is very important.

<sup>31</sup>"Use of Epoxy Compounds With Concrete," Report of ACI Committee 503, *American Concrete Institute Journal* (September 1973).

### Past Applications

ACI Committee 503 reports several types of past applications of epoxies. Epoxy compounds have been used as grouting agents for cracked reinforced-concrete walls and flexural members and deteriorated rubble core masonry, as a patching material for repair of spalled or damaged concrete, or as a bonding medium between hardened concrete and fresh concrete. Thus, epoxies are well suited to seismic strengthening both for repair of damaged members prior to strengthening and for improving the bond between existing and added strengthening materials, i.e., pneumatically applied concrete or fresh concrete.

### Engineering Properties

Several properties of an epoxy formulation are significant in determining its suitability for a given application. Among these are adhesion, effect of temperature variations, resilience, creep and relaxation, rate of hardening, shrinkage, and strength.

#### Adhesion

Epoxy compounds almost invariably provide a good bond with most construction materials which are stronger than the parent material.<sup>32</sup>

#### Effect of Temperature Variations

The effect of temperature on the strength of epoxy is usually not a problem. Generally, strength is not affected until the material attains a temperature of 150°F (66°C). The more common temperature-related problem associated with epoxies relates to thermal expansion and contraction.

In working with reinforced concrete, there is usually no difficulty from thermal expansion or contraction because the steel reinforcing bars and the concrete have very similar coefficients of thermal expansion and contraction. However, the coefficients of thermal expansion and contraction for epoxy are much higher than those of steel and concrete.<sup>33</sup> For some epoxies, the coefficient of thermal expansion may be ten times that of concrete.<sup>34</sup> Hence, when a temperature change occurs, the epoxy must be capable of considerable plastic deformation without cracking either itself or adjacent

concrete. The coefficient of thermal expansion of epoxy may be reduced, however, by adding certain mineral fillers (e.g., silica, limestone).<sup>35</sup>

#### Resilience

Many epoxy formulations continue to respond to loading in an elastic manner even though deformations are relatively high.<sup>36</sup>

#### Creep and Relaxation

Many epoxy formulations exhibit significant creep and relaxation.<sup>37</sup> This problem must therefore be considered in choosing a formulation for a particular application.

#### Rate of Hardening

The rate at which an epoxy formulation will harden is a function of the ingredients, their mixing ratios, and the temperatures of the ingredients of the epoxy and the material to which the epoxy is being applied.<sup>38</sup> The rate of hardening is also quite sensitive to curing procedures.<sup>39</sup> Due to variations in curing conditions, laboratory test data may not reliably predict the rate of hardening obtained in the field.

#### Shrinkage

For most epoxy formulations, shrinkage can be as low as 0.001 percent, if the proper formulation is used.

#### Strength

Like other physical properties, the compressive, tensile, and shear strengths of epoxy vary widely according to the particular formulation. However, epoxies can easily be made stronger in tension and compression than concrete, so strength is not usually a problem. Table 1 provides the measured strengths for the epoxy formulations used in the repair of several bridges in New York State. The data in the table illustrate the high strengths than can be obtained.

#### Alteration of Properties

The characteristics of epoxy compounds are often altered to support a specific application by the addition of various inert inorganic fillers,<sup>40</sup> such as calcium

<sup>32</sup> American Concrete Institute Journal.

<sup>33</sup> American Concrete Institute Journal.

<sup>34</sup> W. R. Lorman, *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976).

<sup>35</sup> American Concrete Institute Journal; and Lorman.

<sup>36</sup> American Concrete Institute Journal.

<sup>37</sup> American Concrete Institute Journal.

<sup>38</sup> American Concrete Institute Journal.

<sup>39</sup> Lorman.

<sup>40</sup> Lorman.

**Table 1**  
**Examples of Epoxy Strength for Several Bridges**  
**in New York State\***

**A**

**Chillon and Bear River Bridges**

**Compressive Properties**

As unfilled resin tested according to ASTM D 695	Compressive strength, 11,930 psi Compressive modulus, 489,000 psi
As a filled system containing three parts by volume silica sand tested according to ASTM C 109	Compressive strength, 12,900 psi Compressive modulus, 1,500,000 psi

**Tensile Properties**

As an unfilled system tested according to ASTM D 638	Tensile strength, 5450 psi Tensile modulus, 227,000 psi
--	--

**B**

**New York Thruway Bridge, Amsterdam, NY**

**Compressive Properties at 75°F**

As unfilled resin tested according to ASTM D 695	Compressive strength, 5370 psi Compressive modulus, 125,000 psi
As a filled system containing three parts silica sand tested according to ASTM C 109	Compressive strength, 8060 psi Compressive modulus, 700,000 psi

**Tensile Properties at 75°F**

As an unfilled system tested according to ASTM D 638	Tensile strength, 2570 psi Tensile modulus, 111,000 psi Tensile elongation, 16.5 percent
--	--

\*Reprinted by permission of the American Concrete Institute from R. J. Schutz, "Epoxy Adhesives in Prestressed and Precast Concrete Bridge Construction," *American Concrete Institute Journal* (March 1976), SI conversion factors: 1 psi = 6.9 kPa;  $(^{\circ}\text{F} - 32)/9 = ^{\circ}\text{C}$ .

carbonate, magnesium silicate, calcium silicate, talcs, clays, or metallic oxides. Possible effects of these fillers include reduction of cost, strength, brittleness, and shrinkage and improvement of wearability, compressive strength, and Young's modulus.

**Examples of Properties for Epoxy Compounds**

Tables 2 through 5 indicate the range of properties possible with epoxy compounds. The tables include physical properties, mechanical properties and some chemical properties. Table 6 lists the standard tests for determining various properties of epoxy compounds.

**Guidelines for Application**

General guidelines regarding surface preparation, mixing procedures, curing, and quality control of epoxy

compounds together with detailed guidelines for three specific applications are presented below.

**Surface Preparation<sup>41</sup>**

Several general rules for preparing surfaces for epoxy application are presented below which are quite important to achieving proper bond between the hardened epoxy and the original material:

1. The surface must be newly exposed concrete. The final surface should be abraded so that the small

<sup>41</sup>Much of the information in this and the following two subsections is drawn from "Use of Epoxy Compounds with Concrete," Report of ACI Committee 503, *American Concrete Institute Journal* (September 1973).



**Table 2**  
**Ranges of Various Engineering Properties of**  
**Typical Cured Commercial Polyamide Epoxy Resin\***

Rigid Epoxy Resin				Physical Property at 75 ± 5° F	Flexible Epoxy Resin	
<i>min</i>	No Filler <i>max</i>	<i>min</i>	Mineral Filler <i>max</i>		<i>min</i>	<i>max</i>
1.11	1.40	1.60	2.40	Specific gravity	1.05	1.35
				Moisture absorption (1/8 in. thickness), wt gain in 24 hours	0.05	1.00
0.08	0.21	0.04	0.10	Clarity		transparent
	transparent		opaque			
Rigid Epoxy Resin				Mechanical Property at 73 ± 5° F	Flexible Epoxy Resin	
<i>min</i>	No Filler <i>max</i>	<i>min</i>	Mineral Filler <i>max</i>		<i>min</i>	<i>max</i>
1,040	13,000	3,000	13,000	Tensile strength (direct), ultimate, psi	1,400	10,000
3	8	>1	3	Tensile elongation, ultimate, %	20	60
average 2,000		1,300	2,000	Bond strength (in ten- sile shear), psi	—	—
400	500	500	650	Bond strength (in com- pressive shear) psi	—	—
6,000	29,000	10,000	35,000	Compressive strength, ultimate, psi	1,000	14,000
5,800	21,000	7,000	15,000	Flexural strength, ultimate, psi	1,000	13,000
average 23		23	28	Impact strength (falling ball), ft-lb	—	—
0.2	1.0	0.3	0.5	Impact strength (Izod), ft-lb/in. of notch	0.5	7.0
190,000	512,000	300,000	1,800,000	Compressive Young's modulus (static) psi	—	200,000
—	698,000	—	—	Compressive Young's modulus (dynamic), psi	—	—
150,000	523,000	300,000	1,000,000	Tensile Young's modulus (static) psi	1,000	350,000
210,000	540,000	400,000	1,600,000	Flexural Young's modulus (static) psi	120,000	1,270,000
79	87	89	91	Hardness (Shore D)	—	—
75	110	85	120	Hardness (Rockwell M)	50	100
17	50	10	22	Coefficient of linear thermal expansion, 10 <sup>-6</sup> in./in./°F	11	56

\*From W. R. Lorman, *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976). SI conversion factors: 1 in. = 25.4 mm; 1 psi = 6.9 kPa; 1 ft-lb = 14.59 N/m; 1 in./in./°F = 0.56 mm/mm/°C.

**Table 3**  
**Ranges of Maximum Ambient Temperatures for**  
**Satisfactory Continuous Service of Typical**  
**Cured Commercial Polyamide-Cured Epoxy Resin**

Rigid Epoxy Resin		Flexible Epoxy Resin	
No Filler	Mineral Filler		
from 175°F	to 190°F	from 175°F	to 200°F
		from 100°F	to 125°F

\*From W. R. Lorman, *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976). SI conversion factor:  $(^{\circ}\text{F} - 32)/9 = ^{\circ}\text{C}$ .

**Table 4**  
**Physical and Chemical Reactions of Typical Cured**  
**Commercial Polyamide Epoxy Resin (Rigid)\***

Effect of	Epoxy Resin Containing No Filler	Epoxy Resin Containing Mineral Filler
Cyclic wetting-drying	none	none
Cyclic freezing-thawing	none	none
Weak acids	none	none
Strong acids	attacked by some	attacked by some
Weak alkalis	none	none
Strong alkalis	slight	slight
Solvents	none	none
Oils	none	none
Chlorides	none	none
Sulfates	none	none
Sunlight	none	none

\*From W. R. Lorman, *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976).

aggregate is visible on the surface. Acid etching to abrade a surface should be used only as a last resort because the acid could increase the chloride content of the concrete, causing the reinforcement to corrode.

2. The surface must be clean.
3. The surface must be dry. Many epoxies will not bond to moist or wet surfaces.
4. The surface temperature at the time of application must be appropriate (60° to 100°F [16° to 38°C]).

When the surface temperature is below 40°F (4°C), heating is often recommended. The heating should be of a general nature—in essence, a heated enclosure for the surface. Localized heating (e.g., a torch) should not be used, as the resulting surface temperature is too difficult to control.

5. Moisture must not be permitted to rise through the concrete by capillary action.
6. Surface contamination via compressed air supply or water jet must be avoided.

**Table 5**  
**Comparison of Properties of Cementitious Grout**  
**and Epoxy Resin Containing Filler\***

Engineering Property	Portland Cement Grout	Epoxy Resin With Mineral Filler
Compressive strength	Fairly low	High
Flexural strength	Low	High
Elasticity relative to hardened concrete	Similar	Higher
Bond to concrete	Good	Very good
Thermal expansion relative to concrete	Similar	Higher
Shrinkage	High	Very low
Creep	High	Low
Impermeability and frost resistance	Fair	Very good
Resistance to chemical attack	Poor	Very good
Cost of constituents	Low	High
Labor costs	Low	Fairly low

\*From W. R. Lorman, *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976).

7. The final prepared surface should be field tested for adequacy. The ACI Committee 503 report presents two procedures for testing the adequacy of a prepared surface. In the more sophisticated procedure, a 2-in.-(51-mm) diameter pipe cap is bonded to the prepared surface and the cap is pulled away from the surface by a testing instrument. The load for failure is recorded, along with information on whether the failure is a bond failure, a tensile failure of the epoxy, or a failure of the surrounding concrete. In the simplified procedure, aluminum T-sections are applied to the surface and pulled free. The committee report provides details on the execution of either variation of the test method.

#### *Mixing*

Proper mixing of the resin, hardener, and added materials is essential for satisfactory results. The proportions should be accurate to plus or minus 2 percent of those desired.

The components of epoxy are often batch-mixed in a tumbling mixer. A paddle mixer is sometimes used, but air entrapment must be guarded against when using such a device. At times, continuous mixing heads are also used.

When preparing epoxy mortar, one must be certain that the binder thoroughly wets each aggregate particle. When mixing epoxy concrete, the coarse aggregate should be mixed in before the fine aggregate.

Temperature of the components can have an effect on proper mixing. Increasing the temperature causes the viscosity to decrease and the working life of the materials to be shortened. Localized heating of the components may be undesirable, because such heating methods may cause localized regions of the epoxy to reach a temperature at which degradation of the materials begins. Generalized heating is required.

#### *Curing*

An epoxy's hardening rate is an important factor in determining its suitability for a specific job. Hardening periods for various epoxy compounds may vary from a few minutes to several weeks. Several factors in addition to the nature of the components and their relative proportions may influence the rate of hardening. Among these are the temperature of the concrete, the air, and the final mixed compound.

When the hardening rate for a compound must be accelerated, some form of heating is generally under-



**Table 6**  
**Testing Standards for Epoxy Formulations\***

Designation	Title
ERF 1-61	Method of Test for Viscosity of Epoxy Compounds and Related Components.
ERF 2-61	Method of Test for Gel Time and Peak Exothermic Temperatures of Epoxy Compounds.
ERF 3-61	Method of Test for Specific Gravity of Epoxy Compounds and Components.
ERF 4-62	Method of Test for Long-Time Creep of Epoxy Compounds.
ERF 5-62	Method of Test for Flexural Properties of Epoxy Compounds.
ERF 6-62	Method of Test for Tensile Properties of Epoxy Compounds.
ERF 7-62	Method of Test for Flammability of Hardened Epoxy Compounds over 0.050 in. in Thickness.
ERF 8-62	Method of Test for Compressive Properties of Epoxy Casting or Molding Compounds.
ERF 9-62	Method of Test for Hardness of Cured Epoxy Materials.
ERF 10-63	Method of Test for Peel Strength of Epoxy Adhesives.
ERF 11-63	Method of Test for Coefficient of Linear Thermal Expansion of Epoxy Casting Compounds.
ERF 12-64	Method of Test for Linear Shrinkage of Epoxy Casting Resins During Cure.
ERF 13-64	Method of Test for Pot Life of Epoxy Compounds.
ERF 14-64	Method of Test for Dimensional Stability of Epoxy Compounds.
ERF 15-64	Method of Test for Dimensional Stability of Epoxy Compounds.
ERF 16-64	Method of Test for Coverage of Laminating System.
ERF 17-64	Method of Test for Deflection Temperature of Cured Epoxy Resins Under Load.
ERF 18-64	Method of Test for Edgewise Compressive Properties of laminating system.
ERF 19-64	Method of Test for Resistance of Plastics to Chemical Reagents.
ERF 20-66	Method of Test for Shear Strength of Epoxy Compounds.
ERF 21-66	Method of Test for Bearing Strength of Epoxy Compounds.
ERF 22-66	Method of Test for Determination of the Thermal Conductivity of Cured Epoxy Resin Systems.
ERF 23-66	Method of Test for Resistance to Impact by Falling Ball.

ERF = Epoxy Resin Formulators Division of Society of Plastics Industries.

\*Reprinted by permission of Lake Publishing Corporation from *Plastics Design and Processing* (March 1967).

taken. Among the approaches used are infrared heaters to preheat the concrete surface and applied epoxy compound, erecting an enclosure heated by circulating warm air around the completed work, placing a polyethylene film over the completed job, and heating the aggregate before mixing. In general, uniform heating to less than 125°F (52°C) is essential. Direct flame heating is prohibited.

When the hardening rate must be slowed, measures to decrease temperature, or at least prevent a rise in temperature, are employed. Among these measures are protection of the application area from direct sunlight (prior to, during, and after application), placing of the

components in an ice bath to lower their temperature before mixing, and spreading of the epoxy compound during application in a very thin film, creating a high surface-to-volume ratio and allowing for more efficient dissipation of heat produced by the chemical reaction that causes the hardening of the epoxy.

#### *Quality Control*

A major consideration in the use of epoxy compounds for strengthening is how to test for the in-place strength of the epoxy compound. A means of controlling and assuring the quality of the strengthening work is required.

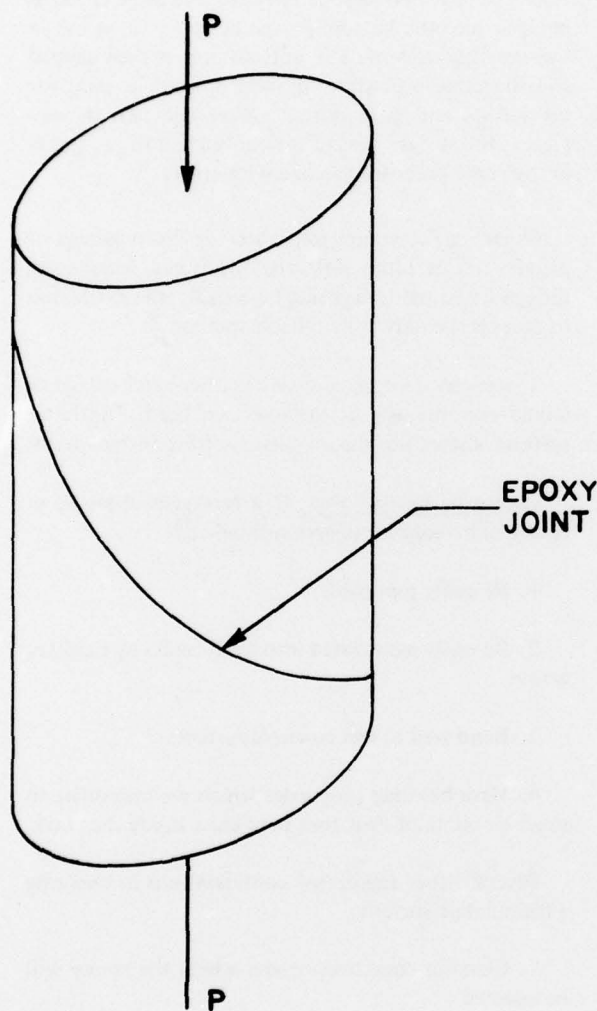


Figure 4. Specimen for Arizona slant shear test.

Ultrasonic testing methods for determining the strength of hardened epoxy have been attempted, but they are not generally reliable enough for quality control or analysis. Extraction of test cores is the only method for determining the strength of in-place epoxy that is both practical and reasonably accurate.

For a given job, screening various epoxy compounds for their bonding qualities may be necessary. One method of accomplishing this screening is the Arizona slant shear test described by Kriegh.<sup>42</sup> A standard concrete test cylinder is cast in two parts, which are then bonded together with the epoxy compound, as shown in Figure 4. The cylinder is tested in compression in the normal manner. Depending on the bonding quality of the epoxy, the failure will be either compressive failure of concrete or bond failure of the epoxy. Kriegh provides details concerning preparing the specimen, performing the test, and analyzing the results.

#### *Epoxy Injection and Grouting*

One major application for epoxy compounds is in filling cracks and voids in deteriorated or poorly constructed concrete or masonry. The effectiveness of epoxy compounds for this application is due mainly to their strength, viscosity, and adhesive qualities.

In repairing cracks, it is important to consider whether the crack is live or dormant.<sup>43</sup> If forces in the structure are causing the crack to propagate, epoxy repair will not be effective. The forces will cause the crack to reform in concrete or masonry adjacent to the repaired crack. Thus, the forces must be relieved before the crack is repaired.

Another consideration is that the cracks must be of a certain size for epoxy repair. Epoxy will not generally penetrate cracks less than 0.001 in. (0.025 mm-) wide.<sup>44</sup>

<sup>42</sup>J. D. Kriegh, "Arizona Slant Shear Test: A Method to Determine Epoxy Bond Strength," *American Concrete Institute Journal* (July 1976).

<sup>43</sup>P. E. Davies, "Plastics in Concrete Technology—Epoxy Resins and Their Uses in Concrete," *Concrete* (January 1970); and W. R. Lorman, *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976).

<sup>44</sup>W. R. Lorman, *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976).

Surface Preparation. The crack for injection should first be thoroughly cleaned; use of a high pressure jet of either water or air is often required.<sup>45</sup> The crack should be dry when the epoxy is actually applied.<sup>46</sup> A shallow groove is sometimes cut along the length of the crack. The exterior surface of the concrete along and to either side of the crack is generally cleaned by either water jet, sandblasting, grinding, chipping, or wire brushing.<sup>47</sup>

Sealing. The first step is to provide a surface sealant over the crack. This step enables the epoxy compound to be injected to a certain internal pressure, assuring that voids in the concrete or masonry are filled. The crack is first V-grooved, and the surface sealant is then applied along the length of the crack. The sealant is generally in one of three forms:

1. High viscosity epoxy resin applied manually over the length of the crack
2. Thermoplastic sealant tape
3. Transparent wax (this allows the level of injected epoxy in the member to be monitored).

The sealant should be able to resist 125 psi (862 kPa) internal pressure without sagging or sloughing off.<sup>48</sup>

Final Preparation. The next step involves providing ports or fixtures through which the epoxy is inserted. Holes 1/4 in. (6 mm) in diameter by 1 in. (25 mm) deep are drilled into the concrete along the crack; metallic nipples are then usually inserted into the holes and secured with epoxy adhesive, although nipples are sometimes deleted so that the injection nozzle is inserted directly into the drilled holes.<sup>49</sup> The spacing of the openings should be approximately equal to the depth of penetration required for the epoxy injection.<sup>50</sup>

Injection Procedure. The epoxy is injected under pressure by pumping, using pressure pot, air- or hand-

operated caulking guns, or hydraulic pumps. The injection must be thorough. It is very difficult to fill voids by reinjection once the epoxy compound has hardened.<sup>51</sup> To avoid such voids, injection begins at the lowermost nipple and works upward. The epoxy is constantly pushed upward against the force of gravity. Low-viscosity epoxy is pumped into the bottom port until the level of the adhesive reaches the next port upward. Inert gas is pumped in at approximately 90 psi (621 kPa) to assure penetration of interior micro-cracks. The gas pressure is released, and more epoxy is pumped into the bottom port until epoxy flows out of the next higher port. The bottom port is then capped and the same procedure, moving upward, is used for the second and third ports.<sup>52</sup> After injection is completed, the surface sealant is removed and the openings of the entry ports are patched with epoxy.<sup>53</sup>

Checking the completed work for thoroughness of penetration is often difficult. Ultrasonic techniques, though often used, may not be reliable; the extraction of cores is the only truly reliable method.<sup>54</sup>

The epoxy compound may be either batch-mixed or mixed continuously at the injection head. The latter method allows the use of faster setting formulations.

Choice of Formulation. In a very general sense, an epoxy to be used for injection should:<sup>55</sup>

1. Be easily pumpable
2. Be easily assimilated into small cracks by capillary action
3. Bond well to wet concrete surfaces
4. Have bonding properties which are insensitive to small amounts of dust that may exist inside the crack.

Several other significant considerations in choosing a formulation include:

1. Climatic conditions under which the epoxy will be injected

<sup>45</sup> "Use of Epoxy Compounds With Concrete," Report of ACI Committee 503, *American Concrete Institute Journal* (September 1973); and Lorman.

<sup>46</sup> *American Concrete Institute Journal*; and Lorman.

<sup>47</sup> Lorman.

<sup>48</sup> Lorman.

<sup>49</sup> Lorman.

<sup>50</sup> *American Concrete Institute Journal*.

<sup>51</sup> Lorman.

<sup>52</sup> Lorman.

<sup>53</sup> *American Concrete Institute Journal*.

<sup>54</sup> *American Concrete Institute Journal*.

<sup>55</sup> *American Concrete Institute Journal*.



2. The length of time for the epoxy to harden (it must not harden before the cracks are fully injected.)

3. The viscosity of the epoxy (the viscosity must be compatible with the crack width.)

4. Whether the concrete or masonry being repaired is moist or dry

5. What the injection port spacing will be.

In all cases, however, the manufacturer's specifications and recommendations for a specific formulation must be consulted to assure compatibility of the formulation with the project.

General Effectiveness. Epoxy compounds will restore the structural member to its full strength. The epoxy will, in general, be stronger than the adjacent concrete or masonry. Subsequent structural damage will occur in the concrete or masonry, rather than the epoxy.<sup>56</sup> Chung<sup>57</sup> discusses the repair of a reinforced concrete beam using epoxy in the laboratory. A virgin beam was loaded to failure. Epoxy was injected into the tension cracks and the region of crushed concrete, and the beam was then retested. The beam failed in a manner (steel yielding followed by crushing of concrete) similar to that in which it failed in the original test. It also exhibited ultimate load and ductility capacity similar to those exhibited in the test performed before repair.

Warner<sup>58</sup> describes a project in which approximately 40 ft (12 m) of a 10-in.- (254-mm) thick reinforced-concrete wall was repaired by epoxy injection. Upon completion of the work, cores were taken through the repaired cracks and in the undamaged concrete adjacent to the repaired cracks. The results indicated:

1. The cores showed complete filling of the cracks
2. The average compressive strength of the cylinders obtained by coring through the repaired cracks was

<sup>56</sup>W. R. Lorman, *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976).

<sup>57</sup>H. W. Chung, "Epoxy Repaired Reinforced Concrete Beams," *American Concrete Institute Journal* (May 1975).

<sup>58</sup>J. Warner, "Restoration of Earthquake Damaged Concrete and Masonry," *Proceedings of the Fifth World Conference on Earthquake Engineering*, Vol 1 (1974), pp 868-871.

5250 psi (36 MPa), compared to 5390 psi (37 MPa) for cylinders obtained by coring into undamaged concrete

3. Of the cylinders tested in direct shear, those taken by coring through the repaired cracks showed an average shear strength of 469 psi (3.2 MPa), while those taken through adjacent undamaged concrete showed an average shear strength of 447 psi (3.1 MPa)

4. None of the cylinders exhibited a failure through the repaired crack.

#### Patching Spalled Concrete

Cases may be encountered in which concrete or masonry on localized areas of the surface of a wall or flexural member has deteriorated or spalled away. In such cases, the member must either be repaired or be considered as possessing only a portion of its computed strength in the structural analysis. Epoxy compounds can be effective for this type of repair. The following paragraphs provide general guidelines for such strengthening.

Surface Preparation. As for other uses of epoxy compounds, the surface must first be cleaned of dust, dirt, and debris using water, jet, compressed air, or sandblast. The surface must be abraded so that small aggregate particles are visible.

Since the surface temperature must be compatible with the epoxy formulation being used, the surface may need to be heated or cooled. Guidelines given previously for heating or cooling epoxy application also apply here.

After the surface has been cleaned, a layer of liquid epoxy binder (with no aggregate) is spread on the prepared surface to assure good bond by penetrating crevices in the surface and assuring complete wetting. For vertical surfaces, additives are added to the epoxy to prevent runoff of the binder.<sup>59</sup>

Patching Procedure. The epoxy is applied to the damaged area, often with apparatus similar to that for injection. Patches more than 5-in. (127-mm) deep are generally built up in layers to avoid heat accumulation in the patch caused by the exothermic nature of the hardening reaction.<sup>60</sup>

<sup>59</sup>"Use of Epoxy Compounds With Concrete," Report of ACI Committee 503, *American Concrete Institute Journal* (September 1973).

<sup>60</sup>*American Concrete Institute Journal*.

Controlling the temperature of the components, including the aggregate, is important for mixing and application. The mix must, of course, be uniform and homogeneous. Both batch mixing and continuous mixing at the application head have been employed in patching projects. In either case, entrapping of air in the patching material must be avoided.

In many cases, heat is applied to the newly placed patch to accelerate curing.<sup>61</sup> As usual, the manufacturer's specifications for the specific formulation must be obeyed.

#### *Bonding Fresh Concrete to Hardened Concrete*

In some cases, increasing the strength of a structure by increasing the thickness of a structural wall or increasing the section of a column may be necessary. If adding the section through conventional casting of concrete is desired, the bond between the old and new sections may be poor. When a good bond is desired for this interface, the new concrete is often cast with a fresh (unhardened) coat of epoxy applied to the old surface. The epoxy and the new concrete cure at the same time, and bond is provided along the interface, since the epoxy compound bonds well to both the old and new materials.

Procedure for Application.<sup>62</sup> The epoxy compound is generally applied to the old surface with a stiff brush. The surface must be thoroughly soaked so that the epoxy penetrates the old material. To assure penetration, the epoxy compound must not be too viscous. If the old material is rather rough, a thick coat of epoxy (thicker than 0.25 mm) may be applied. This application will avoid multiple layers, thus saving labor costs.

The new concrete is placed when the epoxy compound has developed some tack but is not rubbery. If the epoxy reaches a rubbery stage, a new coat must be applied. If vibrators are used in placing the new concrete, appreciable tack must be developed in the epoxy to prevent the vibration from emulsifying the fluid epoxy, leading to runoff.

Choice of Epoxy Compound. The hardening time of the epoxy compound is a very important factor in choosing an epoxy compound for bonding an old and new material. Although the reinforcement can be placed before the application of epoxy (it does not matter

that some epoxy is deposited on the reinforcement), formwork must generally be placed after the epoxy compound is applied. During this period, the epoxy compound must not become rubbery. Achieving this calls for careful design and efficient placement of reinforcement, along with sufficient hardening time for the epoxy compound.

There are epoxy formulations especially designed to be used as a bond coat between old and new material. As always, the manufacturer's recommendations should be consulted. Specially devised epoxy formulations generally are designed to retard pooling of the formulation on application (be thixotropic) and to be capable of forming a 0.4-mm film on the old material without sagging.<sup>63</sup>

#### **Associated Problems<sup>64</sup>**

The preceding sections described the usefulness of epoxy compounds for strengthening cracked or deteriorated structural members, patching over localized damage, and bonding freshly applied concrete to existing concrete. The procedures and precautions necessary to achieve satisfactory results were detailed. This section describes several additional problems and precautions associated with epoxy compounds.

1. The cost for work with epoxy compounds is relatively high in terms of labor. Labor-intensive aspects of the work include surface preparation, mixing, injection, curing, and cleaning.
2. A large number of distinctly different epoxy formulations exists, and documentation of properties of various formulations is often incomplete. Often the choice of the proper formulation for a given job is partially a matter of personal experience. Thus, an engineer on a project must have some background in the use of such materials to use them effectively.
3. There is a distinct shortage of reliable written guidelines for the use of epoxy compounds in various applications.
4. Epoxy compounds and materials used with them often present a hazard to personnel. Many epoxy compounds are allergenic or generate toxic fumes. However,

<sup>61</sup> *American Concrete Institute Journal.*

<sup>62</sup> *American Concrete Institute Journal.*

<sup>63</sup> *American Concrete Institute Journal.*

<sup>64</sup> *American Concrete Institute Journal.*

the hazards vary widely from formulation to formulation, and some formulations are completely safe. Solvents used to clean epoxy from tools or mixers are generally flammable and explosive.

## 5 CHOICE OF A STRENGTHENING SCHEME

When the structural evaluation indicates that a building requires strengthening, the next problem involves choosing a strengthening scheme from the several approaches available.

Structural adequacy is assured by an iterative design process. A reasonable structural strengthening scheme is estimated to obtain a first revision of the structural system. The structural system is then reevaluated in its revised state, applying the same procedure used to evaluate the original structure. If necessary, the structure is revised a second time and evaluated again. Successive revisions are performed until an acceptable strengthening scheme is reached.

The final choice of a strengthening scheme involves more than the evaluation for structural adequacy. Relative costs in terms of both materials and labor must be considered. Local availability of contractors and consultants with experience with a given strengthening method is a consideration. Disruption or other effects of various strengthening approaches on the operation of the facility must be considered, along with the importance of the affected operations. At times, the final choice may be a combination of two or more strengthening schemes, such as adding pneumatically applied, reinforced-concrete walls in the interior of a building and conventionally cast walls on the perimeter of the building. At any rate, the final choice of a strengthening scheme involves the counterbalancing of a number of advantages and disadvantages associated with several possible strengthening approaches, and is thus largely judgmental.

## 6 CONCLUSIONS

Several general conclusions can be drawn from this report:

1. The pneumatic application of concrete is a viable means for strengthening buildings for seismic loading.

2. If satisfactory results are to be obtained with pneumatically applied concrete, the requirements specified in Chapter 3 for forming, surface preparation, application, and reinforcement details must be followed.

3. Strengthening by pneumatic application of concrete has various positive aspects related to impact on the operation of a facility, formwork needs, bond and compressive strengths attained, and ability to reach inaccessible places. There are also negative aspects related to availability of reliable engineering data on behavior under seismic loading, dependency on crew skill, layer thickness limitations, rebound, curing, surface finishing, aggregate grading, and admixture costs. The various characteristics make pneumatic application of concrete suitable for some projects, but unsuitable for others.

4. Epoxy compounds are useful materials for injection into cracked or deteriorated concrete or masonry, patching localized damage in concrete or masonry, and bonding freshly cast concrete to old concrete. However, achieving satisfactory results requires that certain procedures and precautions relative to choice of a compound, mixing, surface preparation, application, quality control testing, and curing be followed when using the compounds.

5. When strengthening with either pneumatically applied concrete or epoxy compounds, the quality of the result is highly dependent upon the general competence and experience of the contractor performing the work.

6. Adding structural walls—whether interior or exterior—to a building increases both the strengths of the structural elements and the earthquake-induced forces in those elements. A complete comparison between induced forces and element strengths must be performed for each strengthening scheme proposed.

## CITED REFERENCES

*Building Code Requirements for Reinforced Concrete*, Standard 318-71 (American Concrete Institute, 1971).



- Chung, H. W., "Epoxy-Repaired Reinforced Concrete Beams," *American Concrete Institute Journal* (May 1975).
- Davies, P. E., "Plastics in Concrete Technology—Epoxy Resins and Their Uses in Concrete," *Concrete* (January 1970).
- "The Guniting Technique," *Concrete Construction* (November 1965).
- Hurd, M. K., *Formwork for Concrete*, Special Publication No. 4 (American Concrete Institute, 1973).
- Krieger, J. D., "Arizona Slant Shear Test: A Method to Determine Epoxy Bond Strength," *American Concrete Institute Journal* (July 1976).
- Lorman, W. R., *Engineering Properties of Epoxy Resin as a Standard Adhesive for Cracked Reinforced Concrete Waterfront Facilities* (Civil Engineering Laboratory, Naval Construction Battalion Center, 1976).
- Lybas, J. M., *Guidelines for Evaluating the Seismic Resistance of Existing Buildings*, Technical Report M-213 (U.S. Army Construction Engineering Research Laboratory [CERL], 1977).
- Orchard, D. F., *Concrete Technology*, Vol 2 (John Wiley and Sons, 1973), pp 380-398.
- Plastics Design and Processing* (Lake Publishing Corporation, March 1967).
- Recommended Lateral Force Requirements and Commentary* (Structural Engineers Association of California, 1974).
- "Recommended Practice of Shotcreting (ACI 506-66)," *ACI Manual of Concrete Practice*, Part 3 (1974).
- Schutz, R. J., "Epoxy Adhesives in Prestresses and Precast Concrete Bridge Construction," *American Concrete Institute Journal* (March 1976).
- Shillstone, J. M., "Site Cast Architectural Concrete—Architectural Surfaces by Shotcreting," *Concrete Construction* (November 1972).
- "Specification for Materials, Proportioning, and Application of Shotcrete," Report of ACI Committee 506, *American Concrete Institute Journal* (December 1976).
- Steenon, H. N., "Fast Set Shotcrete in Concrete Construction," *American Concrete Institute Journal* (June 1974).
- Stockdale, W., *Seismic Design Methods for Military Facilities—Preliminary Recommendations*, Interim Report M-184/ADA027384 (CERL, 1976).
- "Use of Epoxy Compounds With Concrete," Report of ACI Committee 503, *American Concrete Institute Journal* (September 1973).
- Warner, J., "Restoration of Earthquake Damaged Concrete and Masonry," *Proceedings of the Fifth World Conference on Earthquake Engineering*, Vol 1 (1974).

## UNCITED REFERENCES

- Fratt, J. M., *Structural Repair of Earthquake Damaged Buildings*, ASCE National Structural Engineering Meeting Preprint 1973 (April 1973).
- Green, J. K. and W. B. Long, "Guniting Repairs to Fire-Damaged Concrete Structures," *Concrete* (April 1971).
- Handley, W. D., "Guniting," *Concrete* (December 1972).
- Henager, C. H., "A New Wrinkle—Shotcrete Containing Steel Fibers," *Concrete Construction* (August 1975).
- McCafferty, R. M. and M. L. Moody, "An Example of Epoxy Mortar Repair of a Reinforced Concrete Beam-Column Joint," *Proceedings, Fifth World Conference on Earthquake Engineering*, Vol 1 (1974), pp 868-871.

Pinkham, C. W., "A Review of the Repair of Two Concrete Buildings Damaged by the San Fernando Earthquake," *American Concrete Institute Journal* (March 1973).

Smith, D. J., "Repair of Earthquake Damaged Underground Reservoir," *Proceedings ASCE-Journal of the Construction Division* (September 1974).

Spracklen, R. W., *Repair of Earthquake Damage at Holy Cross Hospital*, ASCE National Structural Engineering Meeting Preprint 1941 (April 1973).

Strand, D. R., *Earthquake Repairs, Kaiser Hospital, Panorama City, California*, ASCE National Structural Engineering Meeting Preprint 1996 (April 1973).

"Structural Guniting of Cooling Towers at Thrope Marsh Power Station," *Concrete* (March 1968).

## CERL DISTRIBUTION

Ficatiny Arsenal  
ATTN: SMUPA-VP3

US Army, Europe  
ATTN: AEAEN

Director of Facilities Engineering  
APO New York 09403

DARCOM STIT-EUR  
APO New York 09710

West Point, NY 10996  
ATTN: Dept of Mechanics  
ATTN: Library

Chief of Engineers  
ATTN: Tech Monitor  
ATTN: DAEN-ASI-L (2)  
ATTN: DAEN-FEB  
ATTN: DAEN-FESA  
ATTN: DAEN-FEZ-A  
ATTN: DAEN-MCZ-S  
ATTN: DAEN-RDL  
ATTN: DAEN-PMS (12)  
for forwarding to  
National Defense Headquarters  
Director General of Construction  
Ottawa, Ontario K1A0K2  
Canada

Canadian Forces Liaison Officer (4)  
US Army Mobility Equipment  
Research and Development Command  
Ft Belvoir, VA 22060

Div of Bldg Research  
National Research Council  
Montreal Road  
Ottawa, Ontario, K1A0R6

British Liaison Officer (5)  
US Army Mobility Equipment  
Research and Development Center  
Ft Belvoir, VA 22060

Airports and Const. Services Dir.  
Technical Information Reference  
Centre  
KAOL, Transport Canada Building  
Place de Ville  
Ottawa, Ontario Canada K1A0N8

US Army R&S Group (Europe)  
ATTN: AMXSN-E-RM  
FPO NY 09510

Ft Belvoir, VA 22060  
ATTN: Learning Resources Center  
ATTN: ATSE-TD-TL (2)  
ATTN: Kingman Bldg, Library

US Army Foreign Science & Tech Center  
ATTN: Charlottesville, VA 22901  
ATTN: Far East Office

Ft Monroe, VA 23651  
ATTN: ATEN  
ATTN: ATEN-FE-BG (2)

Ft McPherson, GA 30330  
ATTN: AFEN-FED

USA-WES  
ATTN: Concrete Laboratory  
ATTN: Library

USA-CRREL

6th US Army  
ATTN: AFKC-LG-E  
I Corps (ROK/US) Group  
I Corps (ROK/US) Group  
ATTN: EACI-FN

US Army Engineer District  
Saudi Arabia  
ATTN: Library  
New York  
ATTN: Chief, Design Br  
Buffalo  
ATTN: Library  
Pittsburgh  
ATTN: Library  
ATTN: Chief, Engr Div  
Philadelphia  
ATTN: Library  
ATTN: Chief, NAPEN-D

US Army Engineer District  
Baltimore  
ATTN: Library  
ATTN: Chief, Engr Div  
Norfolk  
ATTN: Library  
ATTN: Chief, NAQEN-D  
Huntington  
ATTN: Library  
ATTN: Chief, ORHED-D  
Wilmington  
ATTN: Chief, SAMEN-DS  
Charleston  
ATTN: Chief, Engr Div  
Savannah  
ATTN: Library  
ATTN: Chief, SASAS-L  
Jacksonville  
ATTN: Library  
ATTN: Const. Div  
ATTN: Design Br, Structures Sec.  
Mobile  
ATTN: Library  
ATTN: Chief, SAMEN-D  
Nashville  
ATTN: ORNED-D  
Memphis  
ATTN: Chief, LMED-DT  
Vicksburg  
ATTN: Chief, Engr Div  
Louisville  
ATTN: Chief, Engr Div  
Detroit  
ATTN: Library  
ATTN: Chief, NCEED-T  
St. Paul  
ATTN: Chief, ED-D  
Chicago  
ATTN: Chief, MCCED-DS  
Rock Island  
ATTN: Chief, NCRED-D  
ATTN: Chief, Engr Div  
St. Louis  
ATTN: Library  
ATTN: Chief, ED-D  
Kansas City  
ATTN: Library (2)  
ATTN: Chief, Engr Div  
Omaha  
ATTN: Chief, Engr Div  
New Orleans  
ATTN: Library (2)  
ATTN: Chief, LMED-DG  
Little Rock  
ATTN: Chief, Engr Div  
Tulsa  
ATTN: Chief, Engr Div  
ATTN: Library  
Fort Worth  
ATTN: Library  
ATTN: Chief, SWFED-D  
Galveston  
ATTN: Chief, SWGAS-L  
ATTN: Chief, SWGED-DS  
Albuquerque  
ATTN: Library  
ATTN: Chief, Engr Div  
Los Angeles  
ATTN: Library  
ATTN: Chief, SPLED-D  
San Francisco  
ATTN: Chief, Engr Div  
Sacramento  
ATTN: Chief, SPKED-D  
Far East  
ATTN: Chief, Engr  
Japan  
ATTN: Library  
Portland  
ATTN: Library  
ATTN: Chief, DB-6  
Seattle  
ATTN: Chief, NPSCO  
ATTN: Chief, EN-DB-ST  
Walla Walla  
ATTN: Library  
ATTN: Chief, Engr Div  
Alaska  
ATTN: Library  
ATTN: Chief, NPADE-R

US Army Engineer Division  
Europe  
ATTN: Technical Library  
New England  
ATTN: Library  
ATTN: Chief, "HED"

US Army Engineer Division  
North Atlantic  
ATTN: Library  
ATTN: Chief, NADEN-T  
Middle East (Rear)  
ATTN: MEDED-T  
South Atlantic  
ATTN: Chief, SADEN-TS  
ATTN: Library  
Huntsville  
ATTN: Library (2)  
ATTN: Chief, HNEDED-CS  
ATTN: Chief, HNEDED-SR  
Lower Mississippi Valley  
ATTN: Library  
Ohio River  
ATTN: Library  
ATTN: Chief, Engr Div  
North Central  
ATTN: Library  
ATTN: Chief, Engr Div  
Missouri River  
ATTN: Library (2)  
ATTN: Chief, MRDED-T  
Southwestern  
ATTN: Library  
ATTN: Chief, SWDED-TS  
South Pacific  
ATTN: Chief, SPDED-TG  
Pacific Ocean  
ATTN: Chief, Engr  
ATTN: FM&S Branch  
ATTN: Chief, PODED-D  
North Pacific  
ATTN: Chief, Engr Div

Facilities Engineers  
Ft Campbell, KY 42223  
Ft Hood, TX 76544  
FORSCOM  
Ft Devens, MA 01433  
Ft Lewis, WA 98433 (2)  
Ft Carson, CO 80913  
TRADOC  
Ft Dix, NJ 08640  
Ft Monroe, VA 23651  
Ft Gordon, GA 30905  
Ft Knox, KY 40121  
Ft Sill, OK 73503  
Ft Bliss, TX 79916  
DSCPER  
West Point, NY 10996  
USAIC (2)  
Ft Benning, GA 31905  
USAAVNC  
Ft Rucker, AL 36361  
CAC&FL (2)  
Ft Leavenworth, KS 66027  
AMC  
Dugway, UT 84022  
USACC  
Ft Huachuca, AZ 85613  
HQ, 1st Inf Div & Ft Riley, KS 66442  
HQ, 5th Inf Div & Ft Polk, LA 71459  
HQ, 7th Inf Div & Ft Ord, CA 93941  
HQ, 24th Inf & Ft Stewart, GA 31313

AF Civil Engr Center/XRL  
Tyndall AFB, FL 32401

Little Rock AFB  
ATTN: 314/DEEE (Mr. Gillham)

AFWL/DES  
Kirtland AFB, NM 87117

Naval Air Systems Command  
WASH DC 20360

NAVFAC/Code 04  
Alexandria, VA 22332

Port Hueneme, CA 93043  
ATTN: Library (Code L08A)

Washington, DC  
ATTN: Building Research Advisory Board  
ATTN: Transportation Research Board  
ATTN: Library of Congress (2)  
ATTN: Dept of Transportation Library

Defense Documentation Center (12)

Engineering Societies Library  
New York, NY 10017



Lybas, John M

Methods for seismic strengthening of buildings. --  
Champaign, Ill. : Construction Engineering Research  
Laboratory ; Springfield, Va. : available from  
National Technical Information Service , 1978.

29 p. ill. ; 27 cm. (Interim report - Construction  
Engineering Research Laboratory ; M-249)

1. Earthquakes and building. I. Title. II.  
Series: U.S. Construction Engineering Research Labor-  
atory. Interim report ; M-249.

ED  
78